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Objective and subjective measures of vergence step responses

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Abstract

Dichoptic nonius lines are used for subjectively (psychophysically) measuring vergence states, but they have been questioned as valid indicators of vergence eye position. In a mirror-stereoscope, we presented convergent and divergent step-stimuli and estimated the vergence response with nonius lines flashed at fixed delays after the disparity step stimulus. For each delay, an adaptive psychophysical procedure was run to determine the physical nonius offset required for subjective alignment; these vergence states were compared with objective eye movement recordings. Between both measures of initial vergence, we calculated the maximal cross-correlation coefficient: the median in our sample was about 0.9 for convergence and divergence, suggesting a good agreement. Relative to the objective measures, the subjective method revealed a smaller vergence velocity and a larger vergence response in the final phase of the response, but both measures were well correlated. The dynamic nonius test is therefore considered to be useful to relatively evaluate a subject's ability in disparity vergence.

Keywords: Nonius lines; Vergence eye movements; Disparity; Step response

1. Introduction

The static vergence angle is traditionally measured with the nonius method (Shimono, Ono, Saida, & Mapp, 1998): with horizontally adjustable and dichoptically presented (i.e., one to each eye) nonius targets, one can determine the amount of nonius offset at which they coincide with the principle visual directions of the eyes and thus are perceived as aligned; from this offset, the vergence state can be calculated geometrically. Nonius tests are referred to as psychophysical or subjective since they rely on the subject's perception of the nonius line position. These tests are technically simple and different versions are applied in research and clinical application (Evans, 2002; Fredenburg & Harwerth, 2001; Jaschinski, 2004; Karania & Evans, 2006; Sheedy, 1980). The nonius method can also be used in dynamic conditions when a change of vergence is induced by changing the disparity of the stimulus (Fredenburg & Harwerth, 2001; Jaschinski, 2004; Mallot, Roll, & Arndt, 1996; Popple, Findlay, & Gilchrist, 1998): nonius lines are flashed for a short period of time at a fixed delay after the disparity step stimulus. This requires a series of vergence step responses, in order to apply the necessary psychophysical procedure.

Nonius tests have been questioned as valid vergence indicators since some researchers reported nonius results that deviated from objective measurements with eye movement recording systems (Howard, 2002; Howard & Rogers, 2002; Shimono et al., 1998), e.g., under forced vergence in static viewing conditions, the nonius technique estimated values smaller than the full amount of fixation disparity (Fogt & Jones, 1998a, 1998b). Further, a continuously visible monocular nonius line failed to reflect periodical vergence changes (Erkelens & van Ee, 1997a, 1997b). The latter result showed, that the perceived visual direction of a continuously visible monocular line is influenced by closely adjacent fusion stimuli. This effect of "capture of visual direction" can be reduced by enlarging the spatial separation between the nonius lines and the fusion stimulus (Erkelens & van Ee, 1997a, 1997b) or by flashing the nonius lines (Jaschinski, Jainta, & Schürer, 2006). Thus,

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previously reported caveats for the nonius technique do not mean that subjective vergence tests are generally invalid. Rather, the conditions of testing appear to play a role, particularly since some versions of nonius tests are applied successfully, e.g., for measures of dark vergence (Jaschinski, Jainta, Hoormann, & Walper, 2007) or for clinical measures of fixation disparity (Karania & Evans, 2006).

In clinical testing, objective binocular eye movement recordings are not applicable since they require elaborate instrumentation, test procedures and data analyses, thus, the technically more simple nonius method remains. In order to have valid clinical nonius tests, one needs to know to what extent the results of subjective nonius tests and objective recordings agree in particular test conditions. It is the purpose of our study to compare subjective and objective vergence measures in a dynamic vergence task where nonius lines are flashed at fixed delays after a disparity step stimulus. While previous researchers used a single amount of nonius delay (Fredenburg & Harwerth, 2001; Jaschinski, 2004; Mallot et al., 1996; Popple et al., 1998), we applied a series of nonius delays in order to sample the vergence step response more precisely and to deduce a measure of vergence velocity.

2. Methods

2.1. Participants

The subjects were selected from a combined participants pool: we tested 25 subjects with a minimal visual acuity of 1 (in decimal units) in each eye without correction. Subjects' age ranged from 17 to 28 years (mean $\pm$ *SD*: 21 $\pm$ 3 years). Myopic, hypermetropic, or astigmatic refractive errors did not exceed the amount of 0.5 D (median across subjects: 0.25 D). Each subject gave informed consent before experiments; the research followed the tenets of the Declaration of Helsinki.

2.2. Apparatus and stimuli

Part of the stimuli (nonius lines, targets for calibrating eye movement recordings) had to be presented monocularly; further, a stepwise change in disparity of the fusion stimulus was required. For this purpose, we used a mirror stereoscope (Howard, 2002, p. 62) with two mirrors at right angle and two VDU screens (CRT Sony F500 T9). These screens were placed at a viewing distance of 60 cm, which was actually applied for all stimuli and allows for a direct quantitative comparison of subjective and objective measures. The fixed viewing distance of 60 cm induced a baseline vergence of about 6 deg (slightly depending on the individual inter-pupillary distance), relative to which we presented convergent and divergent disparity step stimuli of 3 deg. The fixation stimulus contained a black frame (370 min arc width $\times$ 268 min arc height; 16.2 min arc stroke width) with a central fixation cross (34.2 $\times$ 34.2 min arc; stroke width 5.7 min arc) and was presented on a white background with a luminance of 33 cd/m^2 at 100 Hz. The monocular nonius lines for the right and left eye were presented above and below the fixation cross; the nonius lines were 64.9 min arc long (16.2 min - arc stroke width) and had a vertical separation of 32.5 min arc.

2.3. Subjective estimation of vergence changes (dynamic nonius test)

The state reached at certain moments in time during the vergence eye movement was estimated subjectively with nonius lines, which appeared for 80 ms at fixed nonius delays after the disparity step stimulus. In order to find the physical nonius offset at perceived alignment for a certain nonius delay, subjects were required to perform a series of 20 trials, i.e., responses to the vergence stimulus and corresponding backward steps. We presented 20 trials in both the convergent and divergent direction that were randomly interleaved (the time scheme of the trials is described in Fig. 1). The duration of the disparity stimulus was 2000 ms and the fixation period (at the baseline vergence stimulus) before a disparity step stimulus varied randomly in the range of 2750–3000 ms.

From trial to trial, the amount of nonius offset was varied according to the adaptive psychophysical procedure Best-PEST (Lieberman & Pentland, 1982). The result of a run was calculated as average nonius offset of the last 15 trials, since these represent estimations of the point of subjective equality; the first 5 data points of the adaptive phase of the Best-PEST procedure were removed.

The vergence state (relative to the baseline stimulus) was calculated as follows:

$$\text{vergence state} = 2 * \arctan\left((d/2 + \mathrm{PD}/2)/s\right) - 2 * \arctan\left((\mathrm{PD}/2)/s\right),$$

with the physical offset d of the nonius lines from physical alignment, the individual inter-pupillary distance PD and the viewing distance s (0.6 m) (Jaschinski-Kruza & Schubert-Alshuth, 1992). Thus, a vergence state of zero means a precise convergence to the baseline stimulus.

2.4. Objective eye movement recording and data analysis

During the complete subjective test procedure, eye movements were recorded with the video-based EyeLink II to track both eyes simultaneously. A chin and forehead rest including a narrow temporal rest was used to minimize head movements. The dark pupil system tracks the centre of the pupil by an algorithm similar to a centroid calculation with a theoretical noise-limited resolution of 0.01 deg (0.6 min arc) and velocity noise of <3 deg/s for two-dimensional eye-tracking (details provided by SR Research Ltd, Osgoode ON, Canada). For our purpose, we used only the horizontal raw data – sampled at a rate of 4 ms – and calibrated each eye separately to transform the screen-coordinates into degrees. Before the series of vergence steps was started, the following monocular calibration procedure was performed: Subjects were requested to carefully fixate calibration targets that appeared (for 1000 ms) randomly at the screen centre or at horizontal displacements of 1.5 or 3.0 deg to the left or to the right with 100 ms temporal gaps; monocular presentations to the right and left eye were randomly interleaved. In order to draw attention to the calibration targets and to facilitate exact fixation, the diameter of the spot initially subtended 1 deg and shrank immediately during 1000 ms to a remaining cross of 8.1 $\times$ 8.1 min arc (stroke width: 2.7 min arc); the remaining cross was visible for additionally 400 ms during which calibration data were stored. These dynamic targets did not induce disturbing afterimages, since they were presented on a bright background. Fig. 2 shows a typical calibration curve that is highly linear, since we used a small range of visual angle (6 deg) relative to 30 deg specified by the manufacturer.

Data streams of eye movements were cut into 1100 ms epochs containing 100 ms before and 1000 ms after the step stimulus. To exclude blinks and extreme version eye movements within each epoch, values greater than twice the horizontal calibration range were eliminated. Then, vergence was calculated as difference between the positions of the two eyes. The epochs were averaged except for the following artifacts: (1) the mean vergence within the last 50 ms of a step response differed from the mean individual sample response by more than $\pm$20% or (2) the vergence velocity exceeded 40 deg/s, which was judged as physiologically not feasible.

2.5. Experimental design

In Experiment 1, we measured convergent and divergent disparity step responses in a sample of 16 subjects. The subjective vergence state reached at certain moments in time during the vergence response was estimated with nonius lines which appeared for 80 ms with onset delays of 0, 100, 200, 300, 400 or 1000 ms relative to the step stimulus (see Fig. 1). A sep-

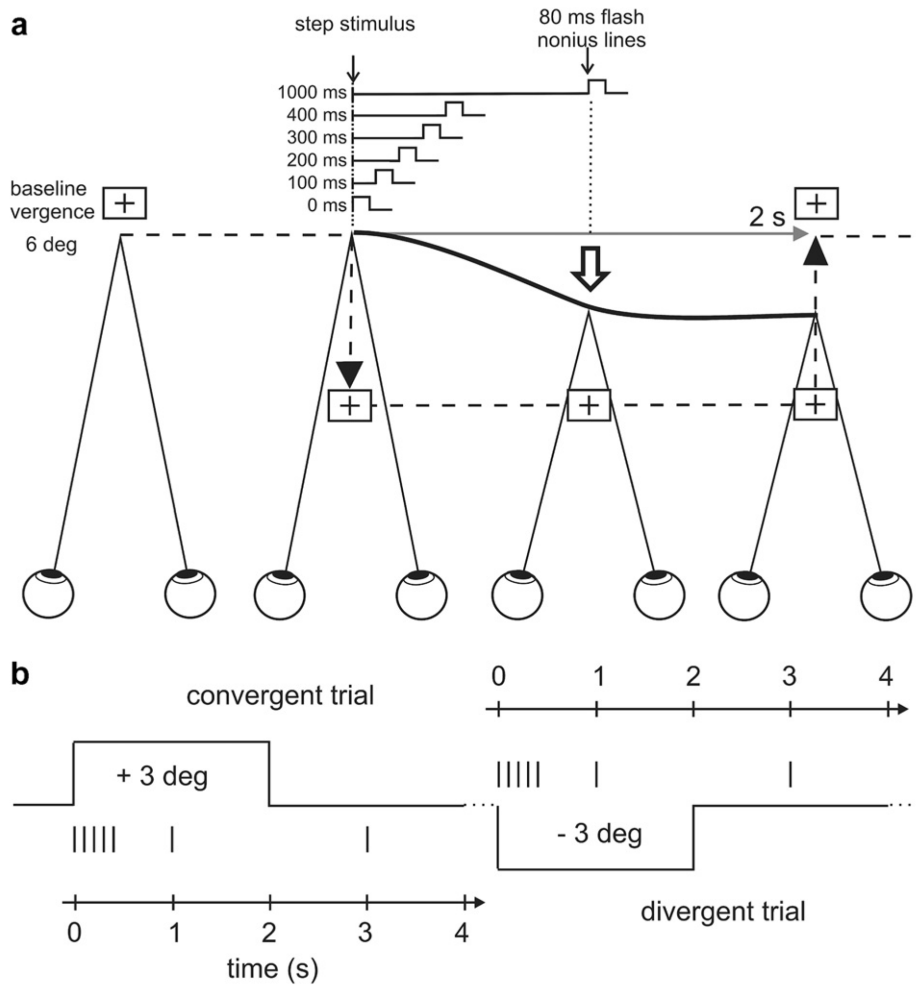

Fig. 1. (a) Time scheme of a single trial showing a convergent disparity step stimulus of 3 deg (relative to a baseline vergence of 6 deg) and the moments in time when the nonius lines were presented relative to a convergent movement. The nonius lines were switched on for 80 ms with a fixed delay relative to the step stimulus onset; this delay was either 0, 100, 200, 300, 400, or 1000 ms in separate runs. In the same way, divergent step responses were induced. At $t = 2$ s, the disparity stimulus was switched off and the fusion stimulus appeared at the baseline vergence. The sigmoidal curve illustrates a vergence eye movement, which saturates at 1000 ms with about half the amplitude of the disparity stimulus. (b) Sequence of one convergent and one divergent disparity step stimuli with interleaved phases to return to baseline vergence. This ticks on the horizontal time axis indicate the moments when nonius lines were presented. In order to find the physical nonius offset of perceived alignment, the trial in (a) was repeated 20 times following an adaptive psychophysical procedure. In Experiment 1, 20 convergent and 20 divergent step stimuli were randomly interleaved. In the control experiment (see Appendix A) we used a nonius delay of 1000 ms after the offset of the disparity stimulus, in order to test whether the baseline vergence had been reached within this period.

arate experimental run was made for each of these six amounts of nonius delay, while 20 convergent and 20 divergent step responses were randomly interleaved. Thus participants were uncertain about the moment of onset (as described above) and the direction of the stimulus (Alvarez, Bhavsar, Semmlow, Bergen, & Pedrono, 2005). The order of these experimental runs was counterbalanced across subjects. The six levels of nonius delay were measured in one session; these measurements were repeated on a separate day and the repetitions were averaged in order to reduce effects of day-to-day fluctuations.

In Experiment 2 we measured only convergent disparity step responses in a sample of 13 subjects. Thus, subjects were aware of the direction of the stimulus; but since the fixation period before a disparity step was randomly varied, they were still uncertain about the moment of onset of the disparity step stimulus (Alvarez et al., 2005). In this experiment, we used nonius delays of 100, 200, 300 and 400 ms which were all tested in one session; the results of three repeated sessions on separate days were averaged.

2.6. Comparison of subjective and objective data

Since the objective and subjective vergence response functions may differ in several aspects, we used three different methods of comparison.

2.6.1. Cross-correlation

Although we used a defined stimulus-related onset and duration of the nonius flashes during the vergence response, we are uncertain about the period of time that is required for retinal and central visual processing until the nonius lines are perceived and effectively will measure the actual vergence state. During this perceptual period, the vergence movement is going to proceed. Thus, we have to consider that the nonius lines will measure the vergence state at a moment in time later than the moment of nonius onset (which is specified in our data presentation). This amount of time shift is unknown and may differ between individuals. A standard procedure to take into account such time shifts in comparisons of time series signals is the maximal cross-correlation (Box & Jenkins, 1976).

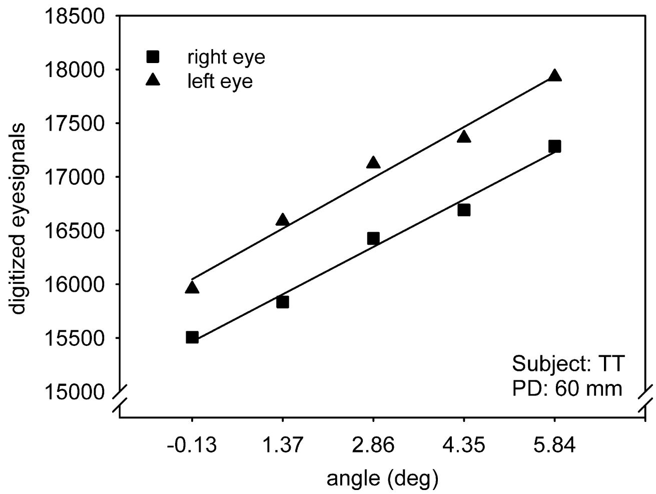

Fig. 2. A typical calibration curve for one subject (TT); fixation targets were presented before the experimental trials in a random sequence and separated for the two eyes (monocularly). Targets appeared sequentially at 5 different positions: at the screen centre or at horizontal displacements of around 1.5 or 3.0 deg to the left and to the right.

Technically, we made the following computational steps.

- The mean vergence state across a 50 ms interval before the step stimulus was calculated as baseline of each trial.
- Relative to this baseline vergence state, we calculated the objective response at moments that corresponded to the amounts of nonius delay in the steep phase of the response (i.e., 0, 100, 200, 300, 400 ms in Experiment 1). These sampled objective data points are illustrated as circles in Fig. 3.
- We calculated a cross-correlation coefficient for each temporal shift of 4 ms of the sampled objective measures (circles in Fig. 3) relative to a fixed position of the subjective measures (triangles in Fig. 3); we used 60 shifts in the range of 0 to 236 ms. The maximum within this series of 60 cross-correlation coefficients quantifies the best similarity of the subjective and objective response curve, after any possible relative time shift is eliminated.

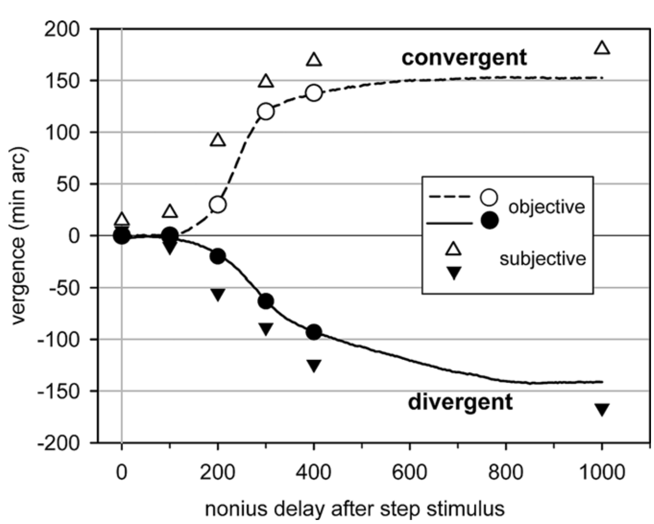

Fig. 3. An example of a subject with a good convergence and divergence. The triangles indicate the subjective estimates corresponding to the 6 nonius delays after the disparity step stimulus. The corresponding objective measures are indicated by circles on the objective curve.

It should be noted that the cross-correlation compares the form of the step responses, irrespective of any possible factor or amplitude offset between the objective and subjective responses; thus, the cross-correlation coefficient reflects neither a possible vergence error adopted before the step response, nor the level of the finally reached vergence state in the later phase of the response. The computation of cross-correlation was based on the following set of data in Experiment 1: One experimental session included experimental runs with five amounts of nonius delay which together gave one subjective response function. The latter was cross-correlated with each of five objective step responses, since for each amount of nonius delay, we averaged the vergence recordings of all 20 trial to get one objective response curve. This was made for each of the two sessions and for 16 subjects. Thus, a pool of $5 \times 2 \times 16 = 160$ maximal cross-correlation coefficients was formed. In Experiment 2, the 4 amounts of nonius delay, 3 sessions, and 13 subjects gave a pool of 156 cross-correlations.

2.6.2. Maximal vergence velocity

The maximal vergence velocity is an important parameter of the course of the step response. From the objective recordings, we calculated velocity profiles using a two-point central difference algorithm (Bahill, Kallman, & Lieberman, 1982) incorporating a central difference of ±1 sampling interval of 4 ms. After using a 50 Hz low pass filter, the smoothed data were scanned for the maximum objective velocity within a time interval of 100 to 650 ms after the step stimulus. For comparison, a maximal subjective vergence velocity was estimated, by finding the maximum of three linear vergence changes corresponding to three pairs of nonius delays (i.e., 100 vs. 200 ms, 200 vs. 300 ms, and 300 vs. 400 ms).

2.6.3. Final vergence state

Since it is known that disparity step responses of some subjects remain uncompleted, we measured the vergence state in the final phase of the response, corresponding to the to longest nonius delay applied, i.e., 1000 and 400 ms (in Experiment 1 and 2, respectively). For the objective measures, we took the average value over the time interval of 950–1000 ms in Experiment 1 and the sampled data point at 400 ms in Experiment 2 (both relative to the step stimulus onset).

3. Results

3.1. Experiment 1

First, we used the cross-correlation to compare the form of the objective and subjective vergence step responses. Fig. 3 shows an example of a subject with good vergence performance. The maximal cross-correlation coefficient between subjective estimates and objective measurements was 0.97 for the convergent and 0.99 for the divergent direction, respectively. The final vergence state indicates that the subjective method overestimated the vergence response by 7.5% for convergence and 14.1% for divergence.

In contrast, Fig. 4 shows a poor performing subject: the missing convergence is shown by both the subjective and objectives measures. Thus, despite the small extent of the response, the maximal cross-correlation was rather high, i.e., 0.73 and 0.83 for convergence and divergence, respectively.

The pooled cross-correlations between objectively and subjectively measured step response gave maximal coefficients ranging from 0.26 to 0.98 (mean ± *SD*: 0.94 ± 0.18) for the convergence and ranging from 0.43 to 0.97 (mean ± *SD*: 0.86 ± 0.10) for the divergence. For both

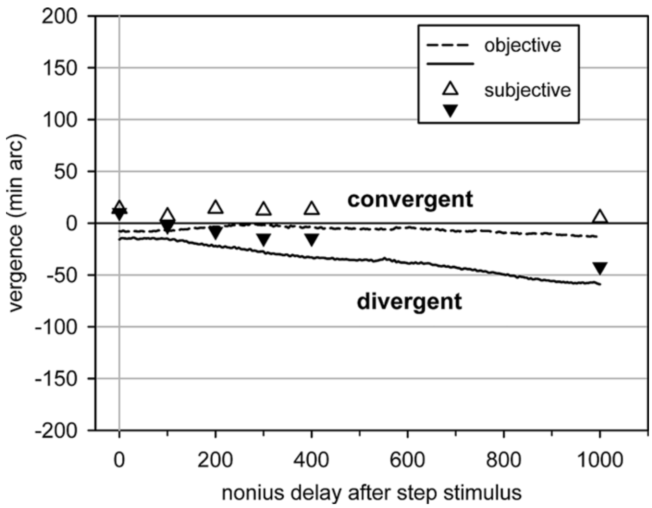

Fig. 4. An example of a subject with a poor convergence and divergence. The triangles indicate the subjective estimates corresponding to the 6 nonius delays after the disparity step stimulus.

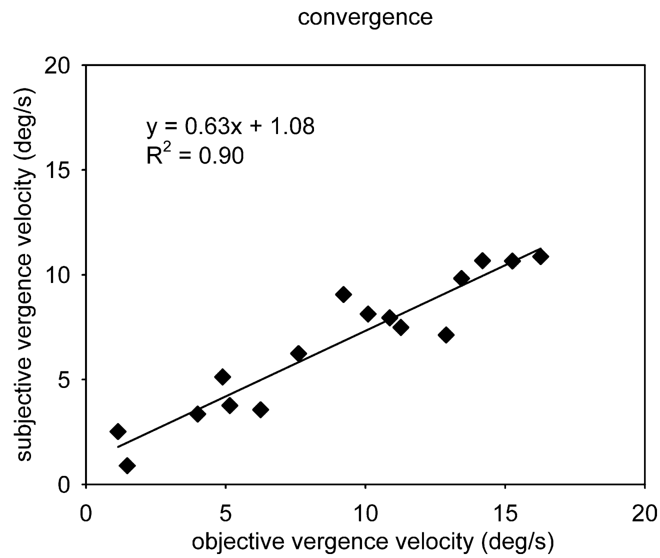

Fig. 5. Experiment 1: Correlation between the subjective vergence velocity estimate and the objective vergence velocity of the mean step response for the convergent step response; the regression equations and R^2 are shown separately.

convergent and divergent eye movements the lowest cross-correlation coefficients belong to two subjects who had a very poor vergence performance and therefore a random-like variation in their subjective estimates. Fig. 4 shows an example of unsystematic subjective estimates scattering around the individual fixation disparity close to zero; when these are compared with a flat curve of objective measurements, poor cross-correlations will result.

Second, we compared the maximal vergence velocities: for the convergent step response, the mean (±*SD*; all mean values are complemented by standard deviations) subjective estimate of the velocity was 6.7 deg/s (±3.2) and the objective vergence velocity was 9.1 deg/s (±1.5). Despite this significant mean difference ($t_{0.05,\ 15} = 4.42$; $p < 0.01$), these two velocities showed a high Pearson correlation coefficient of $r = 0.95$ (see Fig. 5). For the divergent step response, the subjective and objective vergence velocities (4.9 ± 1.8 deg/s and 5.1 ± 2.2 deg/s, respectively) were not significantly different ($t_{0.05,\ 15} = 0.22$) and also showed a high correlation of $r = 0.87$.

Third, we analyzed the final vergence state of the 1000 ms nonius delay. The objective data showed a mean convergent response of 99.6 (±65.2) min arc and a mean divergent response of 90.5 (±36.8) min arc; both are only about half the amount of the stimulus (3 deg = 180 min arc). For the regression analysis, we subtracted the sample mean of subjective and objective measures (comparable to the grand mean of a data pool) from each measure and compared the remaining relative vergence states; this subtraction of the grand mean has some advantages: (1) by regressing the subjective vergence estimates against the objective measures, the absolute regression coefficient reflects the mean difference between the two compared values, (2) this difference is independent of the absolute vergence amplitude reached (and therefore easier to compare between different samples) and (3) the difference is independent of the slope of the subjective–objective regression. For the convergent response, the mean subjective vergence amplitude was 108.4 (±67.6) min arc; only a small, non-significant overestimation of about 8.9 min arc relative to the objective measure was found ($t_{0.05,15} = 1{,}29$; $p = 0{,}21$). Subjective and objective convergence measures in Fig. 6a showed a high correlation ($r = 0.93$; because of the bimodal distribution of data points we additionally calculated the Kendall rank correlation, which was $r_k = 0.78$, i.e., $R_k^2 = 0.61$). For the divergent response, the mean subjective estimate of 118.4 (±35.3) min arc significantly overestimated the objective measure by about 25.4 min arc ($t_{0.05,15} = 5.82$; $p < 0.01$); but again a high correlation is shown in Fig. 6b ($r = 0.86$).

In most subjects, the vergence response was nearly saturated after 400 ms (see Fig. 3 for example). This allows us to test whether the offset between subjective and objective vergence estimates in the later phase of the response is a reliable effect, i.e., whether it appears in a similar strength after 400 ms and after 1000 ms (reported above). For the 400 ms nonius delay, the mean objective convergence of 81.87 (±48.9) min arc was also exceeded by the mean subjective convergent state of 109.68 (±61.2) min arc. The absolute offset of about 27.8 min arc was significant ($t_{0.05,15} = 4.68$; $p < 0.01$) and within the same range as for the divergent state measured with the delay of 400 ms ($t_{0.05,15} = 5.08$; $p < 0.01$; offset: 29.3 min arc).

Thus, in the later phase of the response, the subjective measure overestimated the objectively measured vergence response by about 25 min arc in most condition, except for the 1000 ms nonius delay in the convergent direction.

3.2. Experiment 2

The previous experiment gave the main result that subjective and objective measures were highly correlated, but

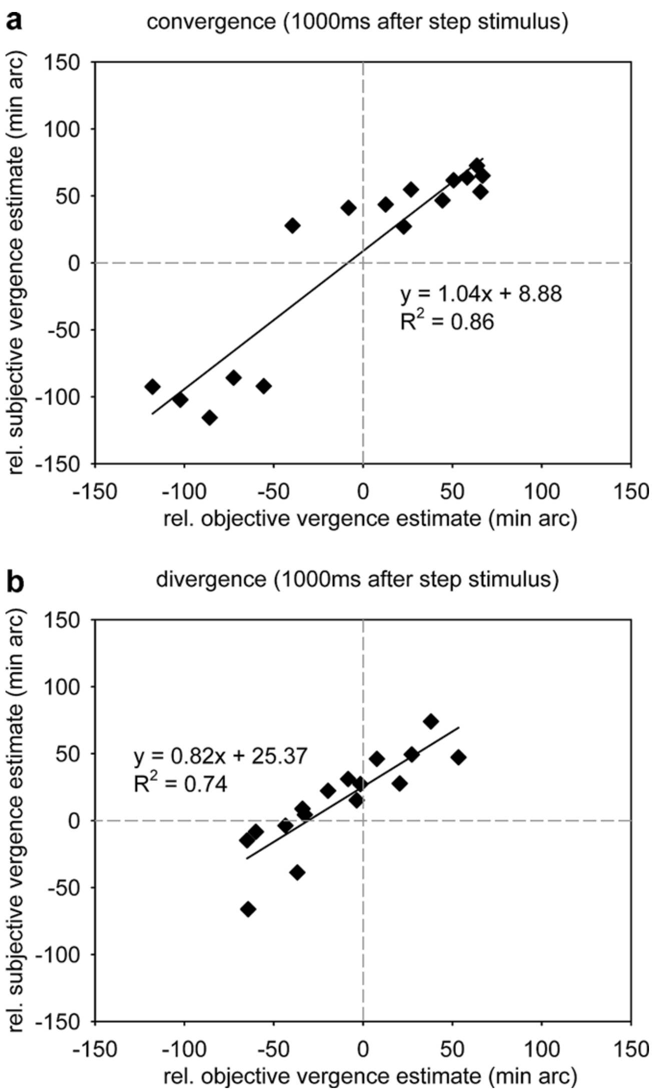

Fig. 6. Experiment 1: Correlation between the subjective vergence estimate and the objective vergence measurement 1000 ms after the step stimulus for (a) the convergent and (b) the divergent step response; for all data the sample mean of 104.1 min arc for convergence and 104.5 min arc for divergence was subtracted before calculating the regression equation. Regression equations and R^2 are shown separately.

that the subjective measure provided an underestimation of vergence velocity and an overestimation of the final vergence state. To see whether these quantitative differences were reliable, a further experiment was performed. Experiment 2 followed the same general procedure, however the design was reduced: only convergent step responses were measured and levels of nonius delays were limited to 100, 200, 300, and 400 ms, since these are located in the steep phase of the subjective response following Experiment 1.

The pooled cross-correlation between objectively and subjectively measured step response gave maximal coefficients ranging from 0.36 to 0.99 (mean ± *SD*: 0.91 ± 0.16) for the convergent eye movement. The mean maximal velocity was 5.2 deg/s (±3.1) for the subjective and 9.7 deg/s (±4.8) for the objective measure; these two velocities

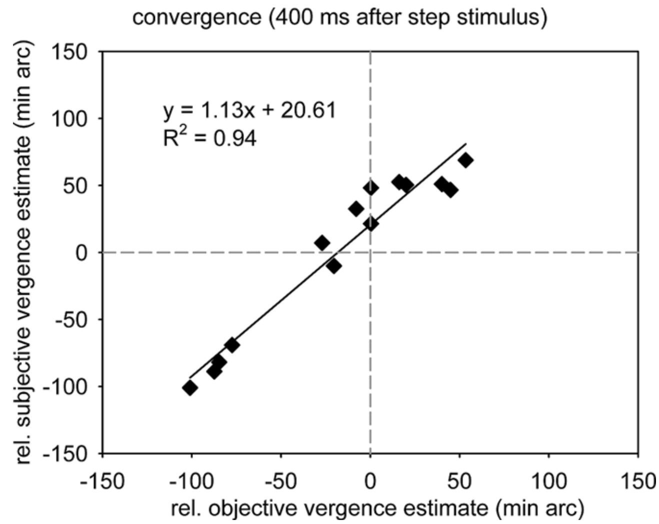

Fig. 7. Experiment 2: Correlation between the subjective vergence estimate and the objective vergence measurement 400 ms after the step stimulus for the convergent step response; for all data the sample mean of 100.9 min arc for convergence was subtracted before calculating the regression equation. Regression equations and R^2 are shown separately.

differed significantly ($t_{0.05,12} = 6.69$; $p < 0.01$), but showed again a high correlation of $r = 0.91$.

For the vergence state that was reached with the 400 ms nonius delay, the objective data showed a mean convergent state of 91.8 (±48.5) min arc. As shown in Fig. 7, the subjective vergence amplitude (mean ± *SD*: 111.4 ± 54.4 min arc) was significantly larger by 20.6 min arc than the objective measure ($t_{0.05,12} = 4.39$; $p < 0.01$), but both were well correlated ($r = 0.97$; additionally we calculated the Kendall rank correlation: $r_k = 0.78$, i.e., $R_k^2 = 0.62$).

4. Discussion

The objective measurements showed mean final vergence amplitudes – measured one second after the step impulse – of just half of the amplitude of the disparity step stimulus of 3 deg. This was the result of partial responses in most subjects; some subjects hardly ever moved their eyes during all presentations. Such individual differences in the amount of disparity vergence responses have been reported previously, with a tendency that some subjects had subtotal responses in either the convergent or the divergent direction (Fredenburg & Harwerth, 2001; Jaschinski, 2004; Jones, 1977). Nevertheless, for a comparison of the subjective and objective estimates of the vergence step response, the finally reached vergence amplitude was of minor interest.

In our subjective test, the subjects judged the nonius line position while the eyes performed a vergence eye movement. This was easily possible; thus, there was no inhibition of perception, as is known to occur during saccadic eye movements. The similarity of objective and subjective measures was tested based on three aspects of the vergence response curve:

1. The high cross-correlation coefficients indicated that the time course of the vergence movement could be estimated well by flashing nonius lines at different delays after the step stimulus. Thus, this procedure allows to estimate the actual vergence state at different moments in time within the vergence movement. The high cross-correlations held for convergent and divergent step responses.
2. The objective maximal vergence velocity values were comparable to previous findings (Hung, Ciuffreda, Semmlow, & Horng, 1994; Tanimoto et al., 2004). The estimated velocity of the eye movements was well correlated between the subjective and objective method, however the subjective method showed a clear underestimation for both vergence directions. This underestimation may be due to the limitation of the subjective method that the sampling interval of 100 ms was too large to detect the moment of maximal velocity.
3. In case of the vergence state reached in the final phase of the response (400 or 1000 ms after the step stimulus), the subjective estimate was also well correlated with the objective measure, but – in contrast to the velocity measure – overestimated the objectively measured vergence response. As stated in the results, care should be taken for non-converging subjects (which were nevertheless categorized as non- or less-converging by both measures).

The differences between objective and subjective vergence measures that we found in the final phase of our dynamic vergence task can be compared with similar differences that have been reported in static conditions of forced vergence. Forced vergence means that the accommodative stimulus is kept constant while the vergence stimulus is changed by varying the absolute disparity of a static fusion stimulus or by introducing prisms. Previous studies have measured the static vergence error (fixation disparity) under forced vergence and found that the subjective fixation disparity was generally smaller than the objective fixation disparity (Fogt & Jones, 1998a). This difference was interpreted to reflect a change in retinal correspondence in a way that Panum's area is shifted towards the fusion stimulus and single vision is therefore possible with larger (objectively measured) vergence errors. We find that – relative to the target vergence state – the subjective vergence error in the later phase of the response is smaller than the objective one (by up to about 25 min arc), on average. Thus, this result corresponds to previous findings in static forced vergence conditions (Fogt & Jones, 1998a; Howard & Rogers, 2002).

The subjective method includes the uncertainty, at which moment in time the flashed nonius lines sample the dynamic vergence response, since we have to consider a certain unknown period (after nonius onset) for neural processing of the nonius line position. However, this perceptual period will have little effect on the three subjective measures that we used. (1) The cross-correlation is independent of this period due to shifting the subjective and objective response function relative to each other. (2) For our subjective estimation of the vergence velocity, we calculated the maximum relative change in vergence across four successive nonius delays; thus, a constant shift of the subjective response curve due to the perceptual period will have no effect. (3) At longer nonius delays of 400–1000 ms, the response function is already rather flat; thus, the resulting subjective vergence measures in this final phase of the response are not much affected by the period for processing the nonius lines.

One may theoretically expect, that the initial vergence state (assumed before the step response) agrees with the vergence angle given geometrically by the viewing distance of 60 cm and the inter-pupillary distance. However, this may not exactly be the case for two possible reasons. First, in a completely static viewing condition, subjects may have a fixation disparity, i.e., individuals may either over-converge (eso fixation disparity) or under-converge (exo fixation disparity) by typically a few minutes of arc. Second, in the present dynamic test of vergence, we induced a series of vergence responses towards the stimulus and subsequent backward movements towards the baseline vergence stimulus. In these conditions, it is possible that vergence might not yet have completely returned to the baseline vergence level (or level of fixation disparity within the 2–3 s provided); rather a residual hysteresis vergence response might have remained when the following step stimulus appeared. This baseline question could – in principle – affect the comparison of the objective and subjective measures of the final vergence state for the following reason. Our objectively recorded responses were always calculated relative to a measured baseline level, i.e., the average across the interval of 50 ms before the step stimulus; this is required also because a relative change in vergence can be measured much more precisely that an absolute vergence state. For the subjective measures, the result of the 0 ms nonius delay may appear to be appropriate as a baseline value; however, this was not the case since it was often shifted into the direction of the stimulus. This is plausible, since the effective moment in time of the subjective measure is later than the moment of nonius onset (as explained above). Thus, without having a measured subjective baseline, our subjective measures were related to the theoretical vergence baseline (as described by the equation in 2.3). In order to test whether this procedure is justified, we made an additional control experiment in a sample of 8 subjects (see Appendix A). It showed that the subjective vergence state (relative to the theoretical baseline) measured 1000 ms after the offset of the step stimulus was smaller than 3 min arc on the average and smaller that 8 min arc in all individual cases. Thus, subjective baseline levels of this order of magnitude are negligible relative to the amplitude of the response of about 100 min arc (on the average).

It should be noted that the initial baseline does not play a role for our two other procedures for comparing of objective and subjective measures for following reasons. The cross-correlation analysis includes a normalization procedure (Box & Jenkins, 1976) and therefore is independent of any difference in amplitude of offset between subjective and objective responses. The calculation of maximal vergence velocity refers to the steep phase of the response curve and therefore does not include the initial vergence.

In conclusion, nonius test results of disparity vergence step responses were not quantitatively identical with objective recordings; further research may find test conditions with reduced discrepancies. However – both measures were well correlated: the proportion of explained variance was in the range of 60–90%. This suggests that the dynamic nonius test allows to identify whether a subject has a relatively high or low disparity vergence performance; this could be sufficient for the assessment of vergence dynamic in the clinical context where objective binocular eye movement recordings are not applicable. e.g., some aspects of asthenopia appear to be related to a weak disparity vergence dynamic (Gall & Wick, 2003), as measured for example with a prism-flipper test (Gall, Wick, & Bedell, 1998). We suggest that the present dynamic nonius test may be a diagnostic alternative: the computer-controlled procedure is independent of motivation effects and has a high test–retest reliability in adults and in children (Jaschinski & König, 2006).

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Appendix A

In our series of convergent and divergent step response trials (see Fig. 1) it is relevant to know whether the eyes actually returned to the baseline vergence before the next step stimulus is presented. Therefore, in this control experiment we used the subjective nonius method to estimate this baseline vergence. We measured the vergence state assumed at a moment in time 1000 ms after the convergent or divergent step response of 3 deg was switched off and replaced by the static fusion stimulus at the baseline vergence angle (corresponding to the 60 cm viewing distance). Separately, we measured the fixation disparity subjectively in a completely static condition: subjects observed the same fusion stimulus that was presented stationary at the 60 cm viewing distance and the adaptive test procedure was used with 20 trials of the nonius lines. We tested a sample of 8 subjects in the same mirror stereoscope; the results of a test and retest were averaged.

Relative to the mean (±*SD*) fixation disparity of 2.04 min arc (±1.95), the baseline vergence after convergence steps was 3.04 min arc (±3.25), i.e., slightly shifted in the positive direction (eso); accordingly, the baseline vergence after divergence steps was 1.14 min arc (±3.68), i.e., slightly more exo than the fixation disparity. This differences suggest that vergence had not yet completely reached

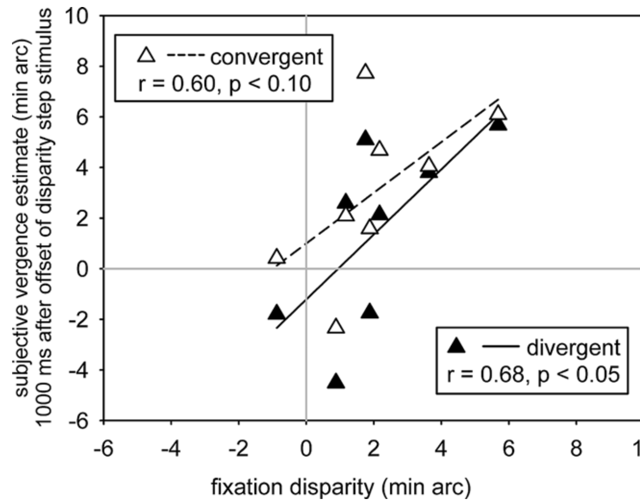

Fig. 8. Control experiment with eight subjects (see Appendix A): Regression between fixation disparity (measured separately in a static viewing condition) and the subjective vergence estimate measured with nonius lines that were flashed 1000 ms after the disparity step stimulus was switched off and replaced by a fusion stimulus at baseline vergence.

the fixation disparity at 1000 ms after offset of the previous convergent and divergent response. But the mean differences of about 1 min arc are only about half the standard deviation of fixation disparity across subjects. The regression in Fig. 8 shows that the baseline vergence after a convergent and after a divergent response was correlated with the fixation disparity. For all three measures, the individual data are in the same range of −5 to +8 min arc.

This control experiment shows that the amount of the individual baseline vergence is predominantly determined by the individual fixation disparity. The previous step response has a minor effect. Furthermore, the range of baseline levels at 1000 ms after stimulus offset is small and negligible relative to the amplitude of the step response that was about 100 min arc (on the average). Additionally, the next step stimulus was presented after longer delays (including a variable gap ranging from 250–750 ms), which provided even more time to recover vergence.

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